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Ignition and combustion characteristics of molded amorphous boron under different oxygen pressures

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ABSTRACT

Ignition and combustion characteristics of amorphous boron (B) have received much attention from researchers in recent decades. A pressurized concentrated ignition experimental system was designed to evaluate the ignition and combustion characteristics of molded B samples. The ignition experiments were carried out under different oxygen pressures (1–9 atm). The condensed combustion products were then analyzed using a scanning electron microscope, an X-ray energy dispersive spectrometer, and an X-ray diffractometer. Furthermore, the complete oxidation rates of the samples were detected by inductively coupled plasma chromatography. As the oxygen pressure increased, the combustion intensity of the samples steadily increased, and the ignition delay time and combustion time both decreased. Under the oxygen pressure of 9 atm, the average ignition delay time and combustion time were 2640 ms and 2596 ms, respectively, and the highest combustion temperature reached 1561.5 °C. The initial diffusion flame on the sample surface was green and the brightest, which was produced by an intermediate combustion product, BO_2 (corresponding molecular emission spectrum wavelength, 547.3 nm). Emission spectra of another intermediate product, BO (431.9 nm) was also detected. Two different types of structures were found in the condensed combustion products of the samples. The first type was the flaky B_2O_3 structure, and the second type was the flocculent structure of incomplete combustion products. The B_2O_3 content in the condensed combustion products increased with the oxygen pressure during combustion. The complete oxidation ratio of the samples also increased with the oxygen pressure, and reached the maximum value of 68.71% under 9 atm. Overall, the samples showed better ignition and combustion characteristics under higher oxygen pressure.

1. Introduction

With the constant demand for higher specific impulse systems, more and more solid propellants have been compounded with metal fuels like magnesium, aluminum, and boron [1]. Compared to magnesium and aluminum, boron has higher gravimetric and volumetric calorific values (58.74 kJ/g and 137.45 kJ/cm^3) [2,3], and is therefore considered to have good application prospects as fuels for solid fueled ramjets [4]. At present, however, the combustion efficiency of boron is greatly limited by problems such as high ignition temperature, high boiling point and melting point, etc. [5], which are in urgent need of solutions. The common forms of boron include crystalline boron and amorphous boron. Research shows that amorphous boron has higher reactivity than crystalline boron [6]. Therefore, the boron fuel used in the solid propellant is usually amorphous boron (hereinafter referred to as B). For half a century [7], researchers have been studying the ignition and combustion characteristics of B and the factors influencing them. As a result, there have been many advances in this field.

Since the ignition temperature of B is high (its onset of combustion temperature is approximately 760 °C in a thermogravimetric experiment [8]), specific ignition devices must be used to ensure the smooth ignition and sufficient combustion of B. Common ignition devices include high-temperature thermobalance, flat flame burner, electric spark igniter, plasma igniter, shock tube, laser igniter, xenon lamp concentrated igniter, and so on [9–15]. Among them, the high-temperature thermobalance uses temperature programmed heating, which makes it difficult to realize a self-sustained combustion. The heat sources of flat flame burner, electric spark igniter, plasma igniter, and shock tube have a very short contact time with the sample. Therefore, these devices mainly apply to studies on single B particle or tiny particles. The laser igniter and the xenon lamp concentrated igniter can heat the sample continuously, thus both can be used for the ignition of B particle groups. The difference

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between the two mainly lies in the area of heating. The laser is a spot light source which only offers spot heating, while the xenon lamp can offer both spot and zone heating by adjusting the concentrator [16,17]. Relative to other zone heating methods, advantages of the xenon lamp concentrated igniter include fast heating rate, high maximum temperature, and good reproducibility. In this work, a spherical large-power short arc xenon lamp (7 kW) is used for the zone heating and ignition of B particle group samples.

Compared to a single B particle, a B particle group has much stronger emission spectrum signals, longer ignition delay time and combustion time [8,18]. These features undoubtedly offer great convenience for collecting data and time resolving during the combustion studies. In earlier studies, the B particle group samples were simply placed in the combustion chamber without any pressing [17]. This method of sample preparation is procedurally easy but has poor repeatability. Other researchers have prepared B particles into pills or gels by mixing with other materials such as oxidizers and binders [3,19]. However, the addition of other materials complicates the research object, as it may influence the ignition and combustion characteristics. A special sample preparation method was used in the present work, which involved pressing the B particle group samples into cylindrical tablets. This method not only ensures both repeatability and purity, but also offers convenience for collection and subsequent analysis of the condensed combustion products. Therefore, it is suitable for laboratory studies.

A pressure chamber was designed to change the operating pressure during the combustion of our samples. The designed pressure chamber is suitable for the xenon lamp concentrated igniter, and can provide a pressure range of 1–9 atm (typical pressure range in the afterburner of a solid rocket ramjet [16]). In addition, a fiber optic spectrometer, a color high speed camera, and an infrared thermo detector were used together for the real-time combustion diagnosis. For the condensed combustion products, a scanning electron microscope, an X-ray energy dispersive spectrometer, and an X-ray diffractometer were used to study the microstructure and composition changes. In addition, inductively coupled plasma chromatography was used for detecting the complete oxidation ratio of the samples (simultaneously considering the gas-solid two-phases). The ignition and combustion characteristics of molded B under different oxygen pressures were therefore comprehensively obtained in this work. The results are expected to provide a reference for the wider application of B fuels in the solid propellants.

2. Experimental section

2.1. Materials

The B sample used in this study was obtained from Baoding Zhongpuruituo Technology Co., Ltd., China. The purity and size range of the B sample were 99% and 0.5–1.5 μm, respectively. A manual tablet press was used for tableting the sample particles into cylindrical tablets before experiments. The diameter of the tablet was 8 mm, the thickness was 1.5 mm, and the average packing fraction was 46.4%. The tablets were then placed on square W slices with edge length of 30 mm and thickness of 1 mm (Fig. 1).

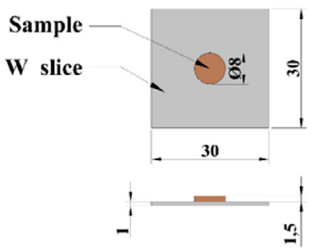

Fig. 1. Sample and W slice.

2.2. Devices and methods

The system used in this study is named as the pressurized concentrated ignition experimental system. Its setup is shown in Fig. 2.

The pressurized concentrated ignition experimental system consists of four parts, namely, the pressure chamber module, the xenon lamp ignition module, the combustion diagnosis module, and the control module. The pressure chamber module contains a pressure chamber and a lift platform. There is a sample holder in the center of the pressure chamber, on which the W slice was placed during experiments. The top of the chamber is the entrance for the xenon lamp light, and is made of quartz glass. On one side of the pressure chamber is a quartz glass window, and on the other side, are three equidistant measuring holes. The gas inlet and outlet are also on the side of the chamber, by which we can adjust the operating atmosphere and pressure. Furthermore, in case of excessively high temperature, the chamber is water-cooled. The heating source of the xenon lamp (ANHONGDA, China, AHD7000W) ignition module is a spherical short arc xenon lamp. An ellipsoidal cold light mirror is used for concentrating the xenon lamp light. The center of the sphere is fixed on the first focal point of the spheroid, and the sample holder of the pressure chamber is placed on the second focal point by adjusting the lifting platform. Three electric fans are used for cooling the two heads of the xenon lamp. The combustion diagnosis module includes a fiber optic spectrometer, a color high speed camera, an infrared thermo detector, and a thermocouple. The infrared thermo detector (measuring range 600–1800 °C) was field calibrated before experiments to adjust its measuring angle and distance. The fiber optic spectrometer, color high speed camera and infrared thermo detector monitored the ignition and combustion processes of the samples through the quartz glass window. The thermocouple is inserted into the chamber through the second measuring hole. The control module contains a modulated power supply for the xenon lamp and a personal computer. The major function of the module is to control the on-off of the experimental system and realize the real-time reading and saving of data.

In this study, the xenon lamp power was set to 7 kW, and the measured maximum operating temperature in the pressure chamber was approximately 1100 °C. The operating oxygen pressure was set to 1, 3, 5, 7, and 9 atm, respectively. The resolution of the color high speed camera (Redlake, USA, GE4900-T12) was set to 800 × 600 pixels. The frame rate and measuring period were set to 250 fps and 17 s, respectively. For the infrared thermo detector (Changzhou Luming, China, LM-6108), the frame rate and measuring period were set to 50 fps and 25 s. For the fiber optic spectrometer (AvaSpec, Netherlands, AvaSpec-3648-USB2), the frame rate and measuring period were set to 100 fps and 10 s, respectively. The spectra of the xenon lamp background light have to be subtracted before the measurements. The tests were repeated 3 to 5 times to ensure the repeatability.

A field emission scanning electron microscope (Hitachi, Japan, SU-70) and a collateral energy dispersal X-ray spectrometer were used for the micro-morphology analysis of the condensed combustion products. The X-ray diffraction analysis was conducted using an X-ray diffractometer (PANalytical, Netherlands, X' Pert PRO). The range of the diffraction angle was set to 5–90°. In addition, an inductively coupled plasma (Thermo Electron, USA, XSENIES) chromatography instrument was used for B element concentration determination in solutions during the complete oxidation ratio analysis.

3. Results and discussion

3.1. Combustion flame analysis

Fig. 3 shows the images of the sample combustion flames at the brightest moment, which indicates the maximum combustion intensity of the samples. The relative positions of the combustion flame, sample tablet, W slice and sample holder are indicated in Fig. 3 (a). From this image, we can also see that the flame on the sample surface was green.